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Hydrodynamics in Shallow Estuaries with Complex Bathymetry and Large Tidal Ranges

Stephen G. Monismith
Dept of Civil and Environmental Engineering
Stanford University
473 Via Ortega
Stanford, CA 94305-4020
phone: (650) 723-3921 fax: (650) 725-9720 email: monismith@stanford.edu

Award Number: N00014-10-1-0236

LONG-TERM GOALS

Out interest is in understanding how stratification, turbulence, and circulation interact in estuarine flows. It is our hypothesis that the role of stratification in suppressing turbulence is central to this interaction. Thus, a major focus of our work is in finding simple relationships (if possible) connecting local flow conditions to turbulence state and turbulent fluxes. We are also interested in using field data from complex estuarine flows to test circulation models, both in terms of straightforward comparisons/calibration and in terms of improving the ability of circulation models to properly represent the physics of these flows.

OBJECTIVES

This project is focused on using data collected during the July 2006 COHSTREX experiment in the Snohomish River Estuary (SRE) to address the following issues:

(1) Construct the momentum balance through the tidal cycle and including spring neap variations in tidal forcing as well as an assessment of the uncertainty of each term.

(2) Analyze the stratified turbulence data acquired with the ADCPs in the SRE to determine when and where mixing of salt and momentum occur in the system and thius to understand the role of the interaction of stratification and turbulence in shaping flows in the SRE.

(3) Construct an analytical framework for studying residual circulation in macro-tidal estuaries, focusing on simplified geometries and forcing (e.g. constant baroclinic pressure gradient), and use that framework to examine our field data.

(4) Understand the dynamics of what we suppose to be trapping-driven frontogenesis in the complex near-field region of the SRE that was the focus of the 2006 COHSTREX experiment.

APPROACH

During FY2010 our efforts have been focused on further analysis of the data obtained in the July 2006 COHSTREX experiment in the Snohomish River Estuary in Washington. This entails using the data to

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1. REPORT DATE **2010**	2. REPORT TYPE	3. DATES COVERED **00-00-2010 to 00-00-2010**

4. TITLE AND SUBTITLE **Hydrodynamics in Shallow Estuaries with Complex Bathymetry and Large Tidal Ranges**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Stanford University,Dept of Civil and Environmental Engineering,473 Via Ortega,Stanford,CA,94305-4020**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**6**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

construct budgets for salt and momentum that will enable us to understand where and when particular physical processes like tidal straining are important. We also have been focusing on analysis of our data in terms of tidal and intra-tidal variability of the flow when viewed in sigma coordinates, i.e., in coordinates that are defined as a fraction of the instantaneous depth, an analytical framework made necessary by the large variations in depth observed in the Snohomish. This work forms the thesis of Ms. Sarah Giddings whose thesis is co-supervised by the PI and Dr. Derek Fong.

WORK COMPLETED

Our active areas of research in FY2010 have included detailed analysis of both the intratidal variability and the subtidal dynamics in the Snohomish River Estuary (SRE). On the tidal time scale we focused on the evolution of stratification, vertical mixing, and longitudinal dispersion, as well as frontal dynamics. This analysis provided good insight to the dynamics in similar strongly forced, strongly stratified estuarine systems which are prevalent yet less well studied than partially mixed systems. We also have been working on investigating the subtidal variability of the SRE, aiming to extend our understanding of estuarine dynamics to the less well understood strongly forced, strongly stratified, large amplitude regime where common approximations such as a constant horizontal salinity gradient, $\partial S/\partial x$, or a small amplitude, $\eta/h \ll 1$ do not hold.

The work completed in the past year has been incorporated into one submitted manuscript, presentations at several conferences, and two papers in preparation.

RESULTS

Intratidal dynamics – stratification and vertical mixing

Due to the salt-wedge nature of the system, both along-stream advection and concomitant straining of the density field dominate temporal and spatial variations in stratification (Figure 1). The dynamics of the straining and advection vary substantially on both a tidal and a fortnightly time scale leading to strong temporal variability in stratification, vertical mixing, and longitudinal dispersion that differs in important ways from observations in partially-mixed estuaries. In particular, flood tide advection is counteracted by straining and vertical mixing such that stratification, shear, and longitudinal dispersion are minimal. In contrast, ebb-tide straining and advection enhance vertical stratification and vertical shear which enhances longitudinal dispersion and leads to strong ebb-tide interfacial mixing.

Intratidal dynamics – Frontogenesis

Complex bathymetry in the SRE leads to trapping of mid-density water over intertidal mudflats which later converges with dense water in the main channel forming a sharp front. The frontal density interface is maintained via convergent transverse circulations driven by both lateral baroclinic and centrifugal forcing. Importantly, the front leads to enhanced stratification and suppressed vertical mixing at the end of the large flood tide. Despite these local effects, this front does not significantly alter longitudinal dispersion. This frontogenesis mechanism fits within the broader context of bathymetrically driven mechanisms in which varying bathymetry drives lateral convergence and baroclinic forcing and we expect it to occur in other systems, potentially even contributing to longitudinal dispersion in estuaries with larger trapping regions. In this investigation, we employed the entire suite of COHSTREX measurements including numerical simulations, RiverRad, TIR imagery,

REMUS and our other in-situ instruments. The manuscript incorporating the results of this investigation involved collaboration with several other COHSTREX investigators whom are included as authors.

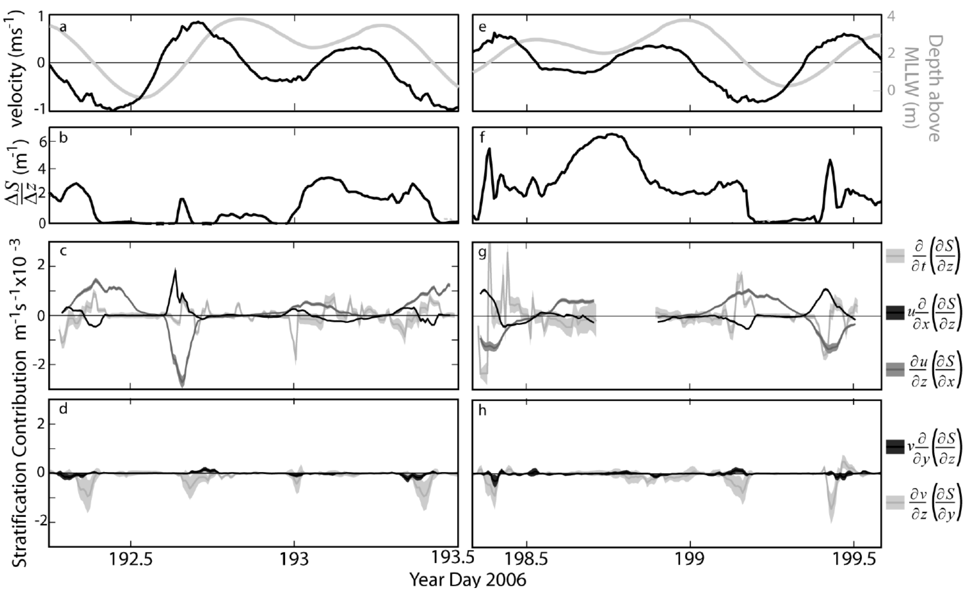

Figure 1: Stratification Evolution at mooring M3B: mean velocity and water level (a, e), top bottom stratification (b, f), and the depth-average of terms contributing to the evolution of stratification (c, g and d, h) for a spring tide (left panels) and neap tide (right panels).

Subtidal dynamics

The most recent area of research has been the investigation of subtidal dynamics. Most estuarine systems exhibit residual (subtidal) circulation driven by the baroclinic forcing, i.e. upstream at depth and downstream at the surface which is considered a critical factor in residual transport processes. Residual circulation is difficult to interpret however in a shallow, macrotidal system where the tidal amplitude is comparable to the mean depth. Profiles of residual circulation and residual density structure are shown in Figure 2 below. We have been working on several approaches including data manipulation and analytical work to try to interpret the observed residual circulation structure, compare it to traditional theories, and the intratidal processes discussed above that contribute to the residual.

The residual circulation does not exhibit the traditional estuarine structure (**Figure 2**a), rather there is out-estuary flow at the bed and peaks mid water column. If we convert our coordinate system to a normalized depth coordinate system, $\sigma = z/D$ where D is the temporally varying total water depth, the residual circulation profile cleans up substantially (**Figure 2**c) and in fact resembles more of a traditional estuarine circulation. Similarly, the density profiles exhibit the more expected residual profiles (**Figure 2**d) as opposed to the z coordinate system where they actually exhibit unstable residual profiles (**Figure 2**b).

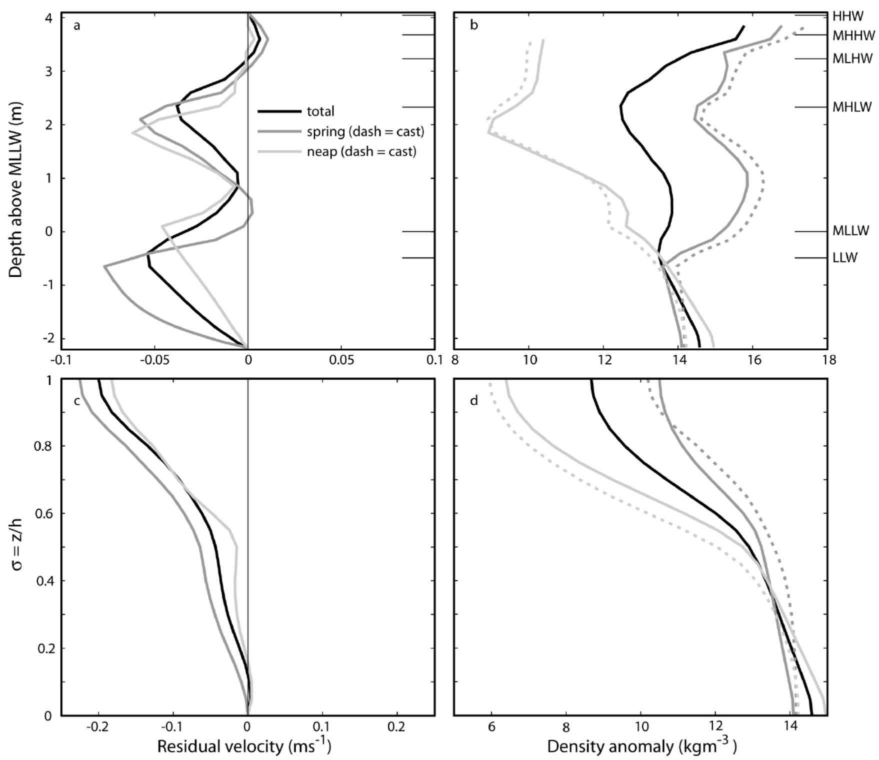

Figure 2: Residual (tidally averaged) circulation (left panels) and density profiles (right panels) in traditional z coordinates (upper panels) and depth normalized, σ coordinates (lower panels).

The normalized depth coordinate system is useful for this type of estuary because it eliminates large amounts of missing data when the water level is beneath high water. We performed an empirical orthogonal function (EOF) analysis on the data in σ coordinates and found that the first two modes represented over 99% of the variability in the data and correlated significantly with the depth averaged velocity and the vertical stratification respectively suggesting that EOF1 represents a barotropic mode while EOF2 represents a baroclinic mode (Figure 3). We note that EOF2 also includes some shear driven by mechanisms other than baroclinic forcing, therefore we will refer to it as a shear mode.

We also included the Stokes wave transport velocity with the Eulerian residuals (4) to approximate the Lagrangian residual. We find that the Stokes wave transport is directed upriver at all depths such that the Lagrangian two-layer circulation (not shown) is stronger than it appears in the Eulerian residuals.

To try to compare the observed residuals to traditional estuarine theory, we have examined analytical solutions to the tidally averaged momentum equations in σ coordinates. Although the σ profiles resemble traditional theory we note that the approximations required to derive the results are often not met in the SRE, particularly near the water surface. Additionally, we have examined the tidally varying momentum equations in detail and hypothesize that like many estuarine systems, this residual is driven by intermittent pulses of two layer circulation created by straining, intratidal variability in vertical mixing, and the strongly temporally varying horizontal salinity gradient that we investigated in our submitted manuscript. Overall it appears that this σ coordinate approach shows promise for interpreting residual circulation in systems with a large tidal amplitude and linking these systems to traditional estuarine theory.

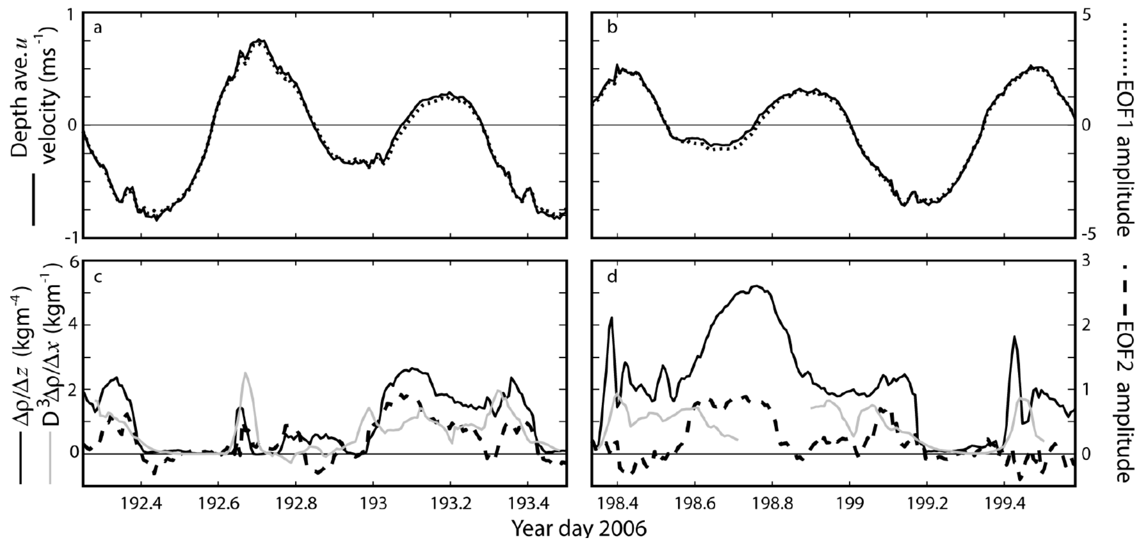

Figure 3: The upper panels show the depth averaged along-stream velocity (black line) along with the amplitude of EOF1 (dotted black line). The lower panels show the vertical stratification (black line), horizontal density gradient multiplied (grey line) along with the amplitude of EOF2 (dashed black line). The left panels show spring tides while the right shows neaps.

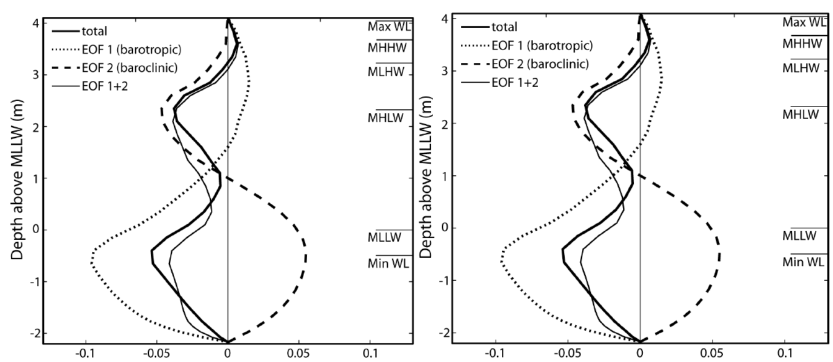

Figure 4. EOF components of the residual circulation

IMPACT/APPLICATIONS

The Navy is responsible for conducting operations in complex coastal environments, such as macrotidal systems found on the west coast of the USA or on the coasts of eastern Africa, northwest Australia or Korea. The work in this project will help build the dynamical framework for these flows that is needed to model them or to interpret data acquired (e.g. remotely) about them.

RELATED PROJECTS

This project is a continuation of the ONR MURI COHSTREX (N00014-05-1-0485) involving researchers from the University of Washington and Stanford.

PUBLICATIONS

Giddings, S.N., D.A. Fong, and S.G. Monismith, "The role of straining and advection in the intratidal evolution of stratification, vertical mixing, and longitudinal dispersion of a shallow, macrotidal, salt-wedge estuary," J. Geophys. Res. (Oceans) (submitted)

Wang, B., S. N. Giddings, O.B. Fringer, E.S. Gross, D.A. Fong, and S. G. Monismith, "Modeling and understanding turbulent mixing in a macrotidal salt wedge estuary," J. Geophys. Res. (Oceans) (submitted)

HONORS/AWARDS/PRIZES

Sarah Giddings received a 2010 Society of Women Engineers teaching award. This award is given to a TA in Engineering by the Stanford chapter of the Society of Women Engineers

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